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Energy prices and economic growth in the long run: Theory and evidence

Istemi Berk [a,*], Hakan Yetkiner [b]

[a] Cologne Graduate School (CGS), Institute of Energy Economics (EWI), EWI Vogensanger Str. 321, University of Cologne, Cologne 50827, Germany
[b] Department of Economics, Izmir University of Economics, Izmir 35330, Turkey

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ABSTRACT

In this paper, we attempt to derive and test the role of energy prices on economic growth. We first developed a two-sector endogenous growth model, based on J Polit Economy 1991; 99:500–521. We modified the model such that consumption goods sector uses energy as an input along with capital. The model allows us to show that the growth rate of energy price has a negative effect on the growth rates of energy use and real GDP. Following this, derived theoretical relationships between energy prices and economic growth and energy consumption were tested empirically using error-correction based panel cointegration tests and panel Autoregressive Distributed Lag (ARDL) approach. We applied this methodology on data of composite energy prices, GDP per capita and energy consumption per capita for sixteen countries for the period between 1978 and 2011. We found significant cointegration between energy prices and real GDP per capita, as well as between energy prices and energy consumption per capita. Moreover, long-run estimates reveal negative and significant effects of composite energy prices on both GDP per capita and energy consumption per capita. We suggest that increasing the share of renewable energy sources in energy consumption would help policy-makers to control permanent long-term increases in consumer energy prices, in turn leading to an increase in economic growth, and hence in welfare. This paper contributes to the literature by highlighting the existence of a previously neglected welfare-improving channel of renewable energy.

Contents

1. Introduction

There has been a plethora of empirical studies on short- or medium-term interactions between energy (especially oil) prices and macroeconomic indicators following the pioneering study of [1]. Although there has been debate over the nature of the relationship, such as non-linearities [2–5] and asymmetries, i.e. differences in response to positive and negative shocks [6–9], there seems to be a consensus on the fact that oil price changes would at least have a particular, if not pivotal, effect on macroeconomic variables.[1]

On the other hand, the impact of (rising) energy prices has never received substantial attention from growth economists, possibly because this has been perceived as a short run issue. The main concentration of the mainstream economic growth

* Corresponding author. Tel.: +49 221 22729 315.
E-mail address: Istemi.Berk@ewi.uni-koeln.de (I. Berk).

[1] Please additionally see: [10–19].

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literature has been on the optimal depletion and the price path of exhaustible resources, following the original study of [20].[2] More recently, the "new" growth economics, i.e. the endogenous economic growth literature, has focused on transition/substitution between energy sources [30–33], directed technical change in an economy with energy sources [34–39] and induced energy-saving technologies and environmental issues [40–42]. Therefore, the issue of effects of energy prices on economic growth seems to be an unexplored area in the theoretical economic growth literature.

For this purpose, we study a stylized model of an economy, in which an energy price-economic growth nexus is developed and tested. In the theoretical part of the paper, we showed that energy price growth has a negative effect on the growth rates of GDP per capita and energy demand by developing a two-sector market economy à la [43]. In our setup, the source of endogenous growth in the economy, i.e. the investment goods sector, uses only physical capital, while the consumption goods sector uses both energy and capital as inputs. Using energy as an input in consumption function has been supported by relatively recent empirical literature (e.g. [18,44,45]). Additionally, it is known that the consumption goods sector has been responsible for the majority of world energy consumption. According to IEA's 2012 World Energy Outlook [46], the combined shares of transportation and residential sectors in total primary energy consumption increased slightly from 60.8% in 1990 to 60.9% in 2008. The report also forecasts that these two sectors combined will remain dominant in energy demand, with a total share varying between 59.4% and 59.8% until 2035.

Our model, further, presumes that the price of energy input is growing at an exogenous rate.[3] Exogeneity in energy, especially oil, prices has recently become a debated issue in the literature. [47] was the first study to stress the bidirectional causality between oil prices and US macroeconomic performance. This reverse causality issue was later empirically quantified by [48], who proposed a methodology to disentangle major oil price movements with respect to three determinant forces: (1) oil supply shocks, (2) demand shocks specific to oil market and (3) shocks due to the global demand for all industrial commodities. The author found evidence that global macroeconomic conditions have been the dominant factor in oil price movements for the post-1973 period. Similarly, more recent studies have suggested that the increase in oil prices between 2003 and 2008 was due to the global business cycle rather than to supply shortfall [49,50]. Therefore, there seems to be a consensus in the literature that endogeneity is a problem in the empirical study of the relationship between oil prices and US macroeconomic indicators. Here, we propose a closed economy and use a broader definition of energy price, i.e. the price of energy services used in the consumption goods sector. While it is clearly possible to endogenize the energy prices in the model, with regards to our research objective, it is more convenient to keep it as an exogenous variable.[4]

The relationships derived in the theoretical part were tested empirically using an error-correction-based panel cointegration test and a panel Autoregressive Distributed Lag (ARDL hereafter) estimation for a group of countries, comprising Austria, Belgium, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Luxemburg, the Netherlands, New Zealand, Portugal, Spain and Sweden.[5]The data on real GDP per capita, energy consumption per capita and composite energy prices cover the period from 1978 to 2011. The test reveals that energy prices have a significant cointegration relationship with real GDP per capita, as well as with energy consumption per capita. Moreover, we found that energy prices have negative and significant long-run effect on both variables. These results provide clear support for the derived theoretical relationships.

The contribution of this paper to the literature is two-fold. First, there exist few studies on energy price-economic growth nexus in endogenous economic growth literature. For example, [34] considering a three-sector model and embedding energy as an input in the intermediate goods sector, have already shown the negative impact of rising energy prices on economic growth.[6] In another study, [52] shows that decrease in energy consumption due to rise in energy prices would promote capital accumulation if the investment effect dominates the lower energy use effect. Thus, higher energy prices do not necessarily hamper the growth process. Second, to the best of the authors' knowledge, although a number of studies analyze the long-term relationship between energy consumption and economic growth, only few studies test the empirical regularity on the long-term relationship between energy price and economic growth. The majority of existing studies use error-correction based models (VECM or VAR) along with the cointegration tests to interpret the relationships for different countries (e.g. [53–56]).[7] Thus, this study explores an untapped area of potential research by applying panel cointegration tests and panel ARDL methodologies to the analysis of the long-term effects of energy prices on economic growth and energy consumption.

The set-up of this paper is as follows. In Section 2 we present the basic model showing that endogenous growth is inversely affected by energy price growth. Section 3 presents the empirical analysis. A summary and some concluding remarks are provided in Section 4.

2. A two-sector endogenous growth model

The model developed in this article is based on a closed economy with no government. We define overall utility of the representative consumer in the economy as $U(C_t)=\int_0^{\infty} e^{-\rho \times t}\, u(C_t)\, dt$, where felicity function is $u(C)=(C^{1-\theta}-1)/(1-\theta)$, C is the consumption level, ρ is the subjective rate of discount and $1/\theta$ represents intertemporal elasticity of substitution. We presume that there are two types of factor of production in the model: broader interpretation of physical capital, K, and energy, E. We further presume that there are also two sectors in the economy, namely investment goods sector and consumption goods sector. Following [43], we define production technology of the investment goods sector as follows:

$$Y_I = A \times K_I \tag{1}$$

In (1), Y_I represents output in investment goods sector, A is overall factor productivity, and K_I, a flow variable, is a broader interpretation of physical capital used in investment good production.

[2] Seminal works in this stream are as follows: [21–29].

[3] Here we implicitly assumed that the energy source is non-renewable, because until recently global energy prices are driven mostly by fossil fuels such as oil, gas, and coal and the renewable energy sources still constitutes smaller portion of global primary energy supply/demand. For instance, in 2011, the share of fossil fuels and renewable energy sources in primary energy demand was 82% and 18%, respectively [46]. Moreover, according to the Hotelling-based reasoning following [20], it is natural to expect that the price of nonrenewable energy sources would increase gradually in the long run due to the scarcity or depletion of resources, although the short-term verification of the rule may not be applicable.

[4] In the Annex, we present the results of the model when energy price is a non-renewable and endogenous.

[5] Please see Section 3 for the rationale for country selection.

[6] [34], which is in fact based on [51], uses energy in intermediate goods sector. Yet, as commonly known, intermediate goods are capital good varieties, thus intermediate goods sector can be considered as investment goods sector.

[7] [57] provides an extensive survey of the literature on energy consumption-economic growth nexus since the seminal study of [58]. Most recent studies mentioned in this survey either use ARDL approach to individual countries (e.g. [59–64]), or panel data error-correction models (e.g. [65–69]).

Consumption good is produced via flow variables physical capital (K_C) and energy (E) under constant returns to scale production technology defined as:

$$Y_C(\equiv C) = K_C^{\alpha} \times E^{1-\alpha} \tag{2}$$

We assume that total physical capital stock $K(=K_I+K_C)$ is fully employed.

Equilibrium process in the investment goods sector from profit equation $\Pi_I = p_I \times A \times K_I - R_I \times K_I$ leads to

$$p_I \times A = R_I \tag{3}$$

In (3), R_I is nominal rental rate (user cost) of physical capital in investment good production and p_I is the price of investment goods. For any K_I, $p_I \cdot A = R_I$ condition must be satisfied. Profit maximization of the consumption goods sector yields inverse demand functions for physical capital (employed in the sector) and energy. In particular, the nominal profit equation $\Pi_C = p_C \times K_C^{\alpha} \times E^{1-\alpha} - R_C \times K_C - R_E \times E$ yields

$$p_C \times \alpha \times K_C^{\alpha-1} \times E^{1-\alpha} = R_C \tag{4a}$$

$$p_C \times (1-\alpha) \times K_C^{\alpha} \times E^{-\alpha} = R_E \tag{4b}$$

In Eqs. (4a) and (4b), R_C is the nominal rental rate (user cost) of physical capital in consumption good production, R_E is the nominal price of energy and p_C is the price of consumption goods. Real energy price is defined as $q = R_E/p_C$, and à la [34], it was considered as growing at a constant rate, $\hat{q} > 0$, and that energy supply is infinite at the given energy price.

No arbitrage condition implies that rental rate of capital in both sectors must be equal. Hence,

$$R_I \equiv R_C \Rightarrow p_I \times A = p_C \times \alpha \times K_C^{\alpha-1} \times E^{1-\alpha}$$
$$\Rightarrow p \times A = \alpha \times K_C^{\alpha-1} \times E^{1-\alpha} \tag{5}$$

In (5), $p = p_I/p_C$ is relative price of investment goods in terms of consumption goods. Then, real user cost of capital (i.e. rental rate) is $RR = p \times A = \alpha \times K_C^{\alpha-1} \times E^{1-\alpha}$. One clear implication of Eq. (5) is that $\hat{p} = (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E}$, where $\hat{p}, \hat{K}_C$ and $\hat{E}$ represent the growth rates of relative price of investment goods (p) and capital (K_C) and energy (E) used by consumption goods sector, respectively. Recall that standard definition of user cost of capital is as follows:

$$RR \equiv (r + \delta - \hat{p}) \times p \tag{6}$$

In (6), r is real interest rate in terms of consumption good price, δ is capital depreciation rate and $\hat{p}$ is the capital loss due to changes in price.

For competitive equilibrium, we also need to examine the representative consumer's optimization problem. To this end, under the assumptions provided so far, the present value Hamiltonian would be as follows:

$$H = e^{-\rho \times t} \times \frac{C^{1-\theta} - 1}{1-\theta} + \lambda\{r \times Assets + q \times E - C\} \tag{7}$$

In (7), *Assets* represents financial stock of the consumer and r is the real interest rate. We hereby assumed that the consumers receive $q \cdot E$ since they are treated as the owner of the energy resource stocks. First order optimization conditions are as follows:

$$\frac{\partial H}{\partial C} = 0 \Rightarrow e^{-\rho \times t} \times C^{-\theta} = \lambda \tag{8a}$$

$$\dot{\lambda} = -\frac{\partial H}{\partial Assets} \Rightarrow \dot{\lambda} = -\lambda \times \{r\} \tag{8b}$$

$$\dot{Assets} = \frac{\partial H}{\partial \lambda} \Rightarrow \dot{Assets} = r \times Assets + q \times E - C \tag{8c}$$

In addition to these conditions, transversality condition, $Lim_{t \to \infty} \lambda(t) \times Assets = 0$, must be satisfied. Eqs. (8a) and (8b) yield

$$\frac{\dot{C}}{C} = \frac{1}{\theta}\{r - \rho\} \tag{9}$$

At equilibrium, financial assets must be equal to physical capital under a closed economy with no government assumption; $Assets = p(t) \times K(t)$. Using this information, we may transform the representative consumer's budget constraint. First, $\dot{Assets} = \dot{p} \times K + p \times \dot{K}$. From (4b), real energy price is $q = (1-\alpha) \times K_C^{\alpha} \times E^{-\alpha}$, and from (5) and (6) $r = A - \delta + \hat{p}$. Hence,

$$\dot{p} \times K + p \times \dot{K} = p \times K \times (A - \delta + \hat{p}) + (1-\alpha) \times K_C^{\alpha} \times E^{1-\alpha} - K_C^{\alpha} \times E^{1-\alpha}$$
$$\Rightarrow p \times \dot{K} = p \times K \times (A - \delta) - \alpha \times K_C^{\alpha} \times E^{1-\alpha}$$

If one substitutes $A \cdot p$ for $\alpha \times K_C^{\alpha-1} \times E^{1-\alpha}$ due to (5) and divide both sides by p, we end up with

$$\dot{K} = (A - \delta) \times K - A \times K_c \tag{10}$$

Hence, the optimization problem of representative consumer yields (9) and (10).

The model can be solved via the first order conditions derived from the optimization problems of representative firms and consumer. First, if we use $r = A - \delta + \hat{p}$ obtained from Eq. (6) in Eq. (9), we get $\dot{C}/C = (1/\theta)\{A - \delta + \hat{p} - \rho\}$. Substituting $\hat{p} = (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E}$ from (5) instead of $\hat{p}$, we find $\dot{C}/C = (1/\theta)\{A - \delta + (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E} - \rho\}$. As $\hat{C} = \hat{Y}_C = \alpha\hat{K}_C + (1-\alpha)\hat{E}$ due to Eq. (2),

$$\alpha\hat{K}_C + (1-\alpha)\hat{E} = \frac{1}{\theta}\left\{A - \delta + (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E} - \rho\right\}$$
$$\Rightarrow (1 - \alpha + \alpha\theta)\hat{K}_C + (1-\alpha)(\theta-1)\hat{E} = A - \delta - \rho$$

Finally, as $\alpha\hat{K}_C - \alpha\hat{E} = \hat{q}$ due to (4b), we obtain

$$\hat{E} = \frac{1}{\theta}\left(A - \delta - \rho - \frac{(1-\alpha+\alpha\theta)}{\alpha}\hat{q}\right) \equiv g' \tag{11a}$$

$$\hat{K}_C = \frac{1}{\theta}\left(A - \delta - \rho - \frac{(1-\alpha)(1-\theta)}{\alpha}\hat{q}\right) \equiv g \tag{11b}$$

$$\hat{C} = \hat{Y}_C = \frac{1}{\theta}\left(A - \delta - \rho - \frac{(1-\alpha)}{\alpha}\hat{q}\right) \equiv \alpha g + (1-\alpha)g' \tag{11c}$$

where $\hat{q}$ is the growth rate of energy prices. Eqs. (11a)–(11c) imply that energy price growth has negative impact on the growth rate of energy use, as also shown by [34]. Note that $(1-\alpha+\alpha\theta)/\alpha > (1-\alpha)(1-\theta)/\alpha$ and that $(1-\alpha+\alpha\theta)/\alpha > (1-\alpha)/\alpha$. We will assume that the condition; $A - \delta - \rho > ((1-\alpha+\alpha\theta)/\alpha)$ holds, hence all growth rates above are positive. We may now solve the rest of the model under this assumption. First of all, using $\hat{p} = (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E}$ equality, one can easily show that

$$\hat{p} = -\left(\frac{1-\alpha}{\alpha}\right)\hat{q}$$

This result can also be expressed as $p(t) = p(0) \times e^{-((1-\alpha)/\alpha)\hat{q} \times t}$.[8] As long as growth rate of energy price is positive, relative price of investment goods in terms of consumption goods $p(t)$ approaches zero. From the equality of $r = A - \delta + \hat{p}$, we may show that

$$r = A - \delta - \left(\frac{1-\alpha}{\alpha}\right)\hat{q}$$

Obviously, real interest rate and hence growth rate of consumption level, $\hat{C}$, are positive if and only if $A - \delta > ((1-\alpha)/\alpha)\hat{q}$.

[8] Recall that growth rate of energy price is exogenously given. Note that we may write the result also as $p(t) = p'(0) \cdot (q(t))^{-(1-\alpha)}$, $p'(0) = p(0)(q(0))^{-(1-\alpha)}$.

Moreover, from Eq. (8b) we get,

$$\hat{\lambda} = -\left\{A - \delta - \left(\frac{1-\alpha}{\alpha}\right)\hat{q}\right\}$$

As $r > 0$, λ must be approaching to zero. If we solve Eq. (10) via integrating factor method, we get

$$K(t) = \frac{A \times K_c(0)}{A - \delta - g} \times e^{g \times t} + const \times e^{(A-\delta)\cdot t}$$

where, *const* stands for constant term. We may easily determine the value of the constant term via the transversality condition. In particular, substituting respective values of λ and $Assets = p \times K$ in transversality condition $Lim_{t\to\infty}\{\lambda(t) \times Assets\} = 0$ yields that *const* must be zero. In addition to this, the condition $A - \delta - g > 0$ must hold for the transversality condition converges to zero at limit.[9] In conclusion, total capital stock path is given by,

$$K(t) = \frac{A \times K_c(0)}{A - \delta - g} \times e^{g \times t} \tag{12}$$

Hence, total capital stock is growing at rate g. Given that initial capital stock is defined exogenously as, $K(0) \equiv K_0 = (A \times K_c(0))/(A - \delta - g)$, to the model, we can determine initial values of flow variables, i.e. $K_c(0)$, $K_I(0)$, $E(0)$.[10]

Finally, let us determine the time path of Real GDP. To this end, note that nominal GDP (NGDP) and real GDP in terms of consumption goods (Y) would be defined as:

$$NGDP = p_I \times Y_I + p_C \times Y_C \Rightarrow Y = p \times Y_I + Y_C$$

One can easily show that real GDP is:

$$Y = const1 \times e^{[\alpha g + (1-\alpha)g'] \times t} \tag{13}$$

In (13), $const1 = p(0) \times Y_I(0) + (K_C(0))^{\alpha} \times (E(0))^{1-\alpha}$, a collection of initial values of the model. In conclusion, total physical capital stock, investment capital and consumption capital all grow at rate g. On the other hand, energy demand grows at rate g' and real GDP and consumption grow at rate $\alpha g + (1-\alpha)g'$, which is the weighted growth rate of energy and physical capital. Energy price growth rate has a negative effect on all growth rates.

3. Testing the long-run effects of energy prices

In this section, we attempted to test the long-run relationship between energy prices, economic growth and energy consumption, that we have derived in theoretical part, cf., Eqs. (11a) and (11c). For empirical purposes, Eqs. (11a) and (11c) can, respectively, be reformulated as[11]:

$$\hat{E} = \beta_{10} + \beta_1 \hat{q} \tag{11a$'$}$$

$$\hat{Y} = \beta_{20} + \beta_2 \hat{q} \tag{11c$'$}$$

where, $\beta_{10} = \beta_{20} = 1/\theta(A - \delta - \rho)$, $\beta_1 = -(1/\theta)((1 - \alpha + \alpha\theta)/\alpha)$ and $\beta_2 = -(1/\theta)((1-\alpha)/\alpha)$. The growth rates $\hat{E}, \hat{Y}$ and $\hat{q}$ can further be defined as $d/dt\ \ln(E)$, $d/dt\ \ln(Y)$ and $d/dt\ \ln(q)$, respectively. Therefore, integrating both sides of both (11a′) and (11c′) will lead

$$\ln(E) = \alpha_{10} + \beta_{10} t + \beta_1 \ln(q) \tag{14a}$$

$$\ln(Y) = \alpha_{20} + \beta_{20} t + \beta_2 \ln(q) \tag{14b}$$

where, α_{10} and α_{20} are the constant terms emerged from integration procedure and t is the time trend component. The Eqs. (14a) and (14b) are the long-run relationships to be tested. To this end, error-correction based panel cointegration test ([70]) and panel ARDL methodology ([71,72]) are applied on balanced panel data, consisting of real GDP per capita (Y), composite energy prices (q) and energy consumption per capita (E), covering the period between 1978 and 2011 for sixteen countries; namely Austria, Belgium, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, Luxemburg, the Netherlands, New Zealand, Portugal, Spain and Sweden.[12]

The countries have been chosen regarding the data availability. Historical data on composite energy prices for each country, defined as real index for households and industry (2005 = 100), have been taken from the International Energy Agency's (IEA) statistics database ([73]).[13] This data set has been provided for OECD countries. Out of these countries we have eliminated the ones, which have been net energy exporters in the subjected period as our main consideration is for imported energy. We, moreover, excluded the United States following the concerns on the endogeneity problem (please see [47]) and some other OECD countries due to data restrictions on other variables; i.e. GDP per capita and energy consumption per capita which have been taken from WDI ([74]). All three variables are used in natural logarithms and indexed taking 2005 as the base year. Table 1 provides the descriptive statistics for all three variables.

As for panels with time dimension larger than the cross-sectional dimension, usual time series problems would emerge. To this end we have tested the variables for unit root using Levin-Li-Chu (LLC) and Im-Pesaran-Shin (IPS) tests proposed by [75] and [76], respectively. Table 2 provides the results of the unit root tests. According to these results, the first differences of all three variables are stationary, i.e. all variables are integrated of order one, $I(1)$. We proceed further with panel cointegration test and panel ARDL as both methodologies are convenient to be applied on $I(1)$ variables.

We have applied error-correction based panel cointegration test proposed by [70]. As correctly noted by [71], this approach is more advantageous than other panel cointegration tests, such as the one proposed by [77], as it avoids the problem of common factor restriction. [78] describes the data generating process assumed by this error-correction test as follows:

$$\Delta y_{i,t} = \delta_i' d_t + \alpha_i y_{i,t-1} + \lambda_i' x_{i,t-1} + \sum_{j=1}^{p_i} \alpha_{i,j} \Delta y_{i,t-j} + \sum_{j=-q_i}^{p_i} \gamma_{i,j} \Delta x_{i,t-j} + \varepsilon_{i,t} \tag{15}$$

where, $y_{i,t}$ is dependent variable, which in our case is either $\ln(Y)$ or $\ln(E)$ and $x_{i,t}$ is the independent variable, which is $\ln(q)$ for our case, for country i in year t. Moreover, while d_t represents the deterministic components, λ_i is defined as $-\alpha_i \beta_i'$ with α_i capturing the seed at which the system $y_{i,t-1} - \beta_i' x_{i,t-1}$ adjusts back to the equilibrium after an unexpected shock. Therefore, if $\alpha_i < 0$ model implies a cointegration between variables and thus the null hypothesis tested is H_0:$\alpha_i = 0$ for all i. [70] proposes four different tests; two of these, namely the group mean tests G_τ and G_a, use alternative hypothesis of H_A:$\alpha_i < 0$ for at least one i. The remaining two, namely, the panel tests P_τ and P_a, use the alternative hypothesis of H_A:$\alpha_i = \alpha < 0$ for all i. The optimal lag and lead lengths of the variables have been chosen via Akaike Information Criteria (AIC). Moreover, following [78] the Kernel width has been

[9] For $\theta > 1$, $((A-\delta)\alpha(\theta-1)+\rho)/(\alpha\theta+1-\alpha)$ is certainly positive. If $\theta < 1$, $\rho > (A-\delta)\alpha(\theta-1)$ must hold.

[10] It is straightforward to show that $E(0) = (1-\alpha)^{1/\alpha}((A-\delta-g)/A)\cdot K_0 \cdot (q_0)^{-(1/\alpha)}$, $K_C(0) = (A-\delta-g)/A \cdot K_0$, $K_I(0) = (\delta+g)/A \cdot K_0$ and $p(0) = (1-\alpha)^{(1-\alpha)/\alpha} \cdot \alpha/A \cdot (q_0)^{-((1-\alpha)/\alpha)}$.

[11] Please note that, the growth rates of output in the consumption goods sector and of composite GDP are the same, i.e. $\hat{Y}_C = \hat{Y}$

[12] Although in the theoretical model assumes closed economy, for empirical applications we use open economies. Yet, since we are dealing with long-run equilibrium, it is rational to expect that those countries have to end up with trade balance thus energy import would be met by export of consumption and service goods.

[13] The composite energy price in [73] is defined as a weighted average of oil products, coal, natural gas and electricity consumed by households and industry.

Table 1
Descriptive statistics of variables (in natural logarithms) over 1978–2011.

Statistics\variables	ln(*Y*)	ln(*E*)	ln(*q*)
Mean	4.368	4.487	4.509
Std. dev.	0.238	0.173	0.186
Minimum	3.492	3.598	3.804
Maximum	4.711	4.785	5.006
No. of countries	16	16	16
No. of observations	544	544	544

Table 2
Panel unit root test results.

Variable	LLC (adjusted *t*-stat.)		IPS (*z*-stat.)	
	Level	First difference	Level	First difference
ln(*Y*)	1.3440	−6.6046***	3.3643	−8.9687***
ln(*E*)	2.9221	−2.8324***	−0.8323	−12.8586***
ln(*q*)	1.5540	−8.1549***	0.6028	−10.5024***

Notes: Tests conducted with constant and trend components.
*** represents significance at 1% level.

Table 3
Panel cointegration test results.

Relationship tested	G_τ	G_α	P_τ	P_α
ln(*Y*) vs. ln(*q*)	−2.842***	−30.345***	−8.820	−17.103***
ln(*E*) vs. ln(*q*)	−2.852***	−20.312***	−12.088***	−18.806***

Notes: Optimal lag and lead lengths selected via AIC are both 1 and optimal Bartlett kernel window width is set to be 3.
*** represents significance at 1% level.

set as $4(T/100)^{2/9}$, where T is the number of observations in time series dimension.

We further proceed with the estimation of Eq. (15) and following the procedure described above; we have presented the results of the four-cointegration tests on Table 3. All test statistics, except for P_τ test on ln(Y) vs. ln(q), lead us to reject the null hypothesis of no cointegration between ln(Y) and ln(q) as well as between ln(E) and ln(q), at 1% significance level.

Having concluded that two cointegrating relationships exist, we have, subsequently, applied Pooled Mean Group (PMG hereafter) and Mean Group (MG hereafter) estimators (i.e. panel ARDL methodology) proposed by [71] and [72]. While MG estimator is based on estimating N times time-series regressions and averaging the coefficients, PMG estimator reveals pooled coefficients. [72] suggests that PMG estimator is more efficient, yet this is only consistent when the model is homogenous in the long run, i.e. the long-run coefficients are equal across countries. MG estimator is advantageous because it is consistent even when the panel data exhibits heterogeneous characteristics, which is common in cross-country studies. As proposed by [72], these estimators lead consistent estimates in larger time dimensional heterogenous panels even when the assumption of strict exogeneity in the regressors is violated. Therefore, although we have accounted for the endogeneity issue when selecting countries to be analyzed, panel ARDL methodology is appropriate with regards to the possible doubts on the endogeneity of composite energy prices with respect to the macroeconomic conditions in the corresponding countries.

Following [79], we have defined ARDL(1,1)[14] dynamic panel specification of (14) as:

$$y_{it} = \lambda_i y_{it-1} + \delta_{10i} x_{it} + \delta_{11i} x_{it-1} + \delta_{20i} t + \mu_i + \varepsilon_{it} \tag{16}$$

and the error-correction parameterization as:

$$\Delta y_{it} = \phi_i (y_{it-1} - \theta_{0i} - \theta_{1i} x_{it} - \theta_{2i} t) + \delta_{11i} \Delta x_{it} + \varepsilon_{it} \tag{17}$$

where; $\phi_i = -(1-\lambda_i)$ is the error-correction term (ECT) speed of adjustment, $\theta_{0i} = \mu_i/(1-\lambda_i)$ is the non-zero mean of cointegration relationship, $\theta_{2i} = \delta_{20i}/(1-\lambda_i)$ and $\theta_{1i} = (\delta_{10i}+\delta_{11i})/(1-\lambda_i)$ is the coefficient of interest, i.e. long-run estimates of elasticity β_1 and β_2 in Eqs. (14a) and (14b), respectively. Obviously, for our case, negative and significant ϕ_i and θ_{1i} should be expected for both two relationships under consideration, i.e. ln(Y) vs. ln(q) and ln (E) vs. ln(q). The estimation results for both relationships and for both estimators (MG and PMG) have been provided on Table 4.

The results are in accordance with the expectations on the coefficients; $\beta_1 < 0$ and $\beta_2 < 0$. MG and PMG estimators estimate negative and highly significant long-run impact of energy price on both GDP per capita and energy consumption per capita. Estimation results reveal also that the effect on GDP per capita (−0.76 for MG estimator and −0.59 for PMG estimator) is higher than that of energy consumption per capita (−0.73 for MG estimator and −0.54 for PMG estimator). These results are consistent with the theory proposed in this article, as well as with the empirical literature. For instance, [14] has estimated the price elasticity of US total energy demand as −0.45 with error bounds of −0.27 and −0.66, moreover, [81] suggested a range between −0.03 and −0.56 for price elasticity of oil demand for different countries. Although our estimates of effect on GDP per capita appears to be higher than that of the literature (e.g. [11,80,81]), they are reasonable as the prior studies mostly concentrated only on the effects of oil prices in the short-run. Moreover, negative and significant ECT terms indicate that the deviations from the long-run path are corrected each period, thus all variables return to their long-run equilibrium.

4. Conclusions and policy implications

In this paper we have presented a two-sector endogenous growth model, following [43]. By including energy as an input in the consumption good sector, we have been able to show that the endogenous growth rate of both output and energy consumption depends negatively on the rate of growth of energy price. These findings are consistent with [34], who use precisely this argument in a study of a three-sector model in which energy is identified as an input in the intermediate-good sector. By testing the theoretical relationships derived by employing error-correction based panel cointegration and panel ARDL methodologies, we found that energy prices have negative and significant impact on both real GDP per capita and energy consumption per capita in the long-run. Thus, both the theoretical and empirical findings suggest significant long-term welfare losses due to the fact that increasing energy prices leads to “under-capacity” or “below-capacity” economic growth.

One policy implication that clearly emerges from this result is the need for policy makers to prevent or at least restrict energy price increases in order to sustain higher long-term economic growth. Yet, this policy recommendation would be superfluous without the introduction of the appropriate channels for the

[14] Lag-length of ARDL model is selected via AIC.

Table 4
Panel ARDL long run and ECT estimates.

	ln(*Y*)		ln(*E*)	
	MG	PMG	MG	PMG
Long-run estimates				
ln(*q*)	−0.7595***	−0.5865***	−0.7308***	−0.5417***
	(0.2826)	(0.1277)	(0.1887)	(0.0479)
t	0.0246***	0.0098***	0.0119***	0.0059***
	(0.0073)	(0.0020)	(0.0041)	(0.0007)
ECT	−0.1831***	−0.0649***	−0.3830***	−0.2067***
	(0.0281)	(0.0105)	(0.0521)	(0.0329)

Notes: Figures in parenthesis are standard errors.
*** represents significance at 1% level.

achievement of this policy goal. Recall the energy price variable in the theoretical part is assumed to follow the Hotelling rule [20], which suggests that the price of nonrenewable energy sources would increase gradually due to scarcity or depletion of resources. This assumption is based on the fact that current global consumer energy prices are largely driven by scarce fossil fuels, such as oil, natural gas, and coal, which constitute 82% of global primary energy demand [46]. Correspondingly, the composite energy prices, used in the empirical part, are also driven by fossil fuels. As defined by [73], these prices are determined as the weighted average of oil products, coal, natural gas, and electricity consumed by households and industry. Therefore, in order to prevent long-term welfare losses due to the rise in composite energy prices, and the consequent below-capacity growth rates, governments should subsidize renewable rather than non-renewable energy sources, as the prices of the latter tend to increase by their very nature in the long run.

There has been extensive literature on the profound positive impacts of renewable energy sources on sustainable development. It has been found previously that the dominance of renewable energy- in energy systems would increase public welfare not only by overcoming environmental constraints and by providing sustainable energy supply (e.g. [82–85] among others), but also by job creation (e.g. [86–88] among others). To the authors' best knowledge, this stream of literature has so far neglected an additional important channel through which renewable energy sources have the potential to contribute to countries' long-term welfare. We suggest that increasing the share of renewable energy sources would directly serve to prevent permanent long-term increases in consumer energy prices, which would lead to increased economic growth. This potential benefit is confirmed by several empirical studies investigating the direct effect of increasing renewable energy consumption on economic growth (e.g. [89–94] among others).

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Appendix A. Solution of the model under endogenous energy price

Suppose now that the energy is a non-renewable one. The non-arbitrage condition would then involve that the real price of energy must increase at the real interest rate[15]

$$\hat{q} = r(t) \tag{A.1}$$

Eq. (A.1) is the well-known Hotelling's rule in it's the simplest form. Now let us use this information in the model. One may recall that we obtained $\alpha\hat{K}_C - \alpha\hat{E} = \hat{q}$ from Eq. (4b), $r = A-\delta+\hat{p}$ from Eq. (6) and $\hat{p} = (\alpha-1)\hat{K}_C + (1-\alpha)\hat{E}$ from Eq. (5). Therefore

$$\alpha\hat{K}_C - \alpha\hat{E} = \hat{q} = r = A-\delta+\hat{p} \Rightarrow$$
$$\alpha\hat{K}_C - \alpha\hat{E} = A-\delta+(\alpha-1)\hat{K}_C+(1-\alpha)\hat{E} \Rightarrow$$
$$\hat{K}_C = A-\delta+\hat{E}$$

If this information is used in Eq. (9), we obtain

$$\frac{\dot{C}}{C} = \frac{1}{\theta}\{A-\delta+\hat{p}-\rho\} \Rightarrow$$
$$\frac{\dot{C}}{C} = \frac{1}{\theta}\left\{A-\delta+(1-\alpha)(\hat{E}-\hat{K}_C)-\rho\right\} \Rightarrow$$
$$\frac{\dot{C}}{C} = \frac{1}{\theta}\{\alpha(A-\delta)-\rho\}$$

Hence,

$$\hat{p} = -(1-\alpha)(A-\delta)$$
$$r = \hat{q} = \alpha(A-\delta)$$
$$\hat{E} = \frac{1}{\theta}[\alpha(A-\delta)(1-\theta)-\rho] \equiv g'$$
$$\hat{K}_C = \frac{1}{\theta}[(A-\delta)(\theta+\alpha(1-\theta))-\rho] \equiv g$$

Interestingly, given that $A-\delta>0$ for a positive real interest rate and energy price growth rate, θ must be less than one. Otherwise, energy demand would be decreasing in time. As $\theta+\alpha(1-\theta)>0$ is always true, growth rate of physical stock employed in consumption good sector is positive as long as $(A-\delta)(\theta+\alpha(1-\theta))>\rho$.

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[15] Suppose that the energy market is a perfectly competitive one and that extraction is costless. Under these assumptions, the representative firm would solve the following maximization problem (cf., [95,96]):

$$\begin{aligned} &Max \quad \int_0^\infty q(t)\times E(t)\times e^{-\int_0^t r(\tau)d\tau} \\ &s.t. \quad \int_0^\infty E(t)dt \le S_0 \\ &\qquad\quad Lim_{t\to\infty}\{q(t)\times E(t)\times e^{-\int_0^t r(\tau)d\tau}\} \end{aligned}$$

where S_0 is the initial stock of the nonrenewable energy. The solution of the isoperimetric calculus of variations problem leads to (12).

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